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# Relativistic electron precipitation bands in the outside radiation environment of the International space station

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ABSTRACT

The Radiation risk radiometer-dosimeter (R3DR2) performed active dosimetry measurements outside the International space station (ISS) during the ESA EXPOSE-R2 missions from October 24, 2014 until January 11, 2016. The 10 s resolution flux and dose rate data were used to find, identify and classify the relativistic electron precipitation bands (PB) (Blake et al., 1996) in the outside radiation environment of the ISS. The PB were identified as rapid (10–40-s) dose rate enhancement from the normal (20–200 μGy $h^{-1}$) outer radiation belt (ORB) level and similar fast return to the same low level. Only PB that have in the time profile dose rates larger than 10,000 μGy $h^{-1}$, identical to flux larger than 4000 $cm^{-2}$ $s^{-1}$, for 10 or more seconds were selected. Sixteen PB were studied. The largest selected PB, delivered in the R3DR2 detector, which was behind 0.3 g $cm^{-2}$ shielding, a dose of 464 μGy for 70 s. The later was larger than the ORB daily average dose rates for 366 days out of 442 days measurements during the analyzed period. The daily average doses inside of the ISS were measured, using the DOSTEL instrument, at an average level of 194 μGy $d^{-1}$ (Reitz et al., 2005). This indicates that only for 70 s, the cosmonaut/astronaut, being on extra vehicular activity (EVA), where they are shielded only by their space suits, will accumulate the equivalent of about 2.5-days dose inside of the ISS. Only 1 PB was identified during the ESA EXPOSE-E mission on ISS in the period February 17, 2008–September 3, 2009, while in the more active geomagnetically EXPOSE-R mission in 2010, 6 PB were registered. Although the obtained PB doses do not pose extreme risks for cosmonauts/astronauts health, being on EVA, they have to be considered as a possible extremely high dose rate source, which requires additional comprehensive investigations.

## 1. Introduction

This paper analyses the space radiation conditions, created by the ORB relativistic electrons, on the ESA EXPOSE-R2 platform, mounted outside the ISS Russian “Zvezda” module. Dachev et al. (2017a), have already published preliminary information for the observed cosmic radiation time profile during the EXPOSE-R2 mission.

The main idea of the paper is to find, identify and classify the relativistic electron precipitation bands (Blake et al., 1996) in the outside radiation environment of the ISS in the period October 24, 2014–January 11, 2016. Short overview of the PB observations outside ISS during the EXPOSE-E (2008–2009) and EXPOSE-R (2009–2010) missions is presented at the end of the paper, too.

### 1.1. ORB characteristics at the ISS altitude

The Van Allen radiation belts are two regions, encircling the Earth, in which energetic charged particles are trapped inside the Earth's magnetic field. Their properties vary according to solar activity and they represent a hazard to satellites and humans in space (Horne et al., 2005). The ORB is located in the altitudinal range from 3.4 to 10 Earth radii above the equator. The ORB population is electrons with energies less than 10 MeV.

In 2001, we have observed, for the first time, relativistic electrons and/or bremsstrahlung in the US laboratory module of the ISS in the data of the mobile dosimetry unit no. 2 (MDU#2). The latter was a part of the Liulin-E094 instrument (Dachev et al., 2002; Reitz et al., 2005). Because of the relatively small fluxes and dose rates, the effect was not fully understood. Later, the relativistic electrons were steadily observed outside the Foton-M2/M3 spacecraft in the periods May 31–June 16, 2005 and September 14–29, 2007, as well as outside the European Columbus module of the ISS in 2008 (Dachev et al., 2009, 2012a; 2012b). The analysis of the absorbed ORB daily doses, measured outside ISS by the R3DE/R/R2 instruments (Dachev et al., 2013, 2015b, 2017a, 2017b) showed that during the quiet geomagnetic conditions they are at very low levels of a few to a few tens of μGy $d^{-1}$ and do not pose any risk for the astronauts at the time of EVA. It is worth underlining that during EVA

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astronauts are shielded only by their space suits, which have shielding characteristics similar to our instruments, i.e. of 0.3 g cm$^{-2}$ (Benton et al., 2006; Cucinotta et al., 2003). The highest ORB daily dose of 2962 μGy d$^{-1}$ was observed with the R3DR2 instrument on 20th of March 2015 at the recovery phase of the geomagnetic storm from March 17. The enhanced, during recovery phase of magnetic storms, ORB daily doses of 2000–3000 μGy d$^{-1}$ are much higher than the other daily sources of galactic cosmic rates (GCR) (80–90 μGy d$^{-1}$) and inner belt protons (400–500 μGy d$^{-1}$).

The additional dose rate, measured with DOSTEL instrument outside the ISS due to the enhanced particle flux (EPF) *(this is the term, which was used for the ORB relativistic electrons flux by* Labrenz et al. (2015)*)*, from 24 September to 8 October2004 was calculated to be ~130 μGy d$^{-1}$. The daily average ORB dose rate, measured with the R3DR2 instrument was more than twice larger (278 μGy d$^{-1}$), for the period October 24, 2014–January 11, 2016. These values can be explained with the larger geomagnetic activity in the period.

The variations, connected with the geomagnetic activity, represented with the (Disturbance Storm Time) Dst index (http://wdc.kugi.kyoto-u.ac.jp/index.html) or solar wind variations, are with the longest time scale of days. During the quiet time, the doses delivered by the relativistic electron flux in the ORB are at very low levels - up too few tens of μGy d$^{-1}$. Relativistic electron flux typically decreases, by two or three orders of magnitude, during the main phase of geomagnetic storms and recovers to or increases beyond the pre-storm level during the recovery phase, within several days (Zheng et al., 2006).

Following Blake et al. (1996), the precipitation bands are typically a few degrees in latitude. These bands are often seen in conjugate locations and on consecutive orbits (Blake et al., 1996), suggesting that their tens of seconds duration (as measured by low Earth orbit (LEO) satellites) is due to their spatial rather than temporal, characteristics. Blum et al. (2013) have shown that the precipitation bands can last up to hours and to contribute significantly to the loss of electrons from the ORB. The rapid electron precipitation is often observed at low altitude on a variety of timescales, ranging from short bursts of less than 1 s (microbursts) to a longer duration precipitation, extending a few degrees in latitude.

Blum et al. (2015) investigated the PB that were observed by SAMPEX/HILT instrument (Baker et al., 1993) during 42 high-speed stream-driven storms in 2003–2005 with an average $Dst_{min}$ of ~35 nT. They found that the PB could occur in all epochs of the storm, with a larger occurrence rate in the recovery phase at L value of 4–5. The magnitude of the PB was also increased in the recovery phase, while the L value of the maximum position slightly decrease below L = 5. Blum et al. (2015) mentioned that the PB may be induced by the electromagnetic ion cyclotron (EMIC) waves, which are observed in the inner magnetosphere, primarily in the afternoon sector.

As R3DR2 exposition time is 10 s, microbursts (Blum et al., 2015) are not observable. Yet, the PB structures were registered. The aim of the paper is to study their occurrences and magnitude during the EXPOSE-R2 mission on the ISS. The observed total doses for the PB are analyzed and characterized. The author firmly believes that the obtained for the first time on ISS PB dose rates can be further used for the radiation risk assessment of the astronauts being on EVA.

## 2. Material and methods

Fig. 1 presents an external view of the R3DR2 instrument, as mounted on the EXPOSE-R2 facility. The R3DR2 instrument is a low mass (0.19 kg), small dimension (76 × 76 × 36 mm) automatic device that measures the solar electromagnetic radiation in four channels and the ionizing radiation in 256 channels. The three solar UV (ultraviolet) and one visible radiation photodiodes are seen in Fig. 1 as small circles on the surface in the central part of the R3DR2 instrument. Their data are not used in this paper. The ionizing radiation detector is located behind the aluminum wall of the instrument and is therefore not visible.

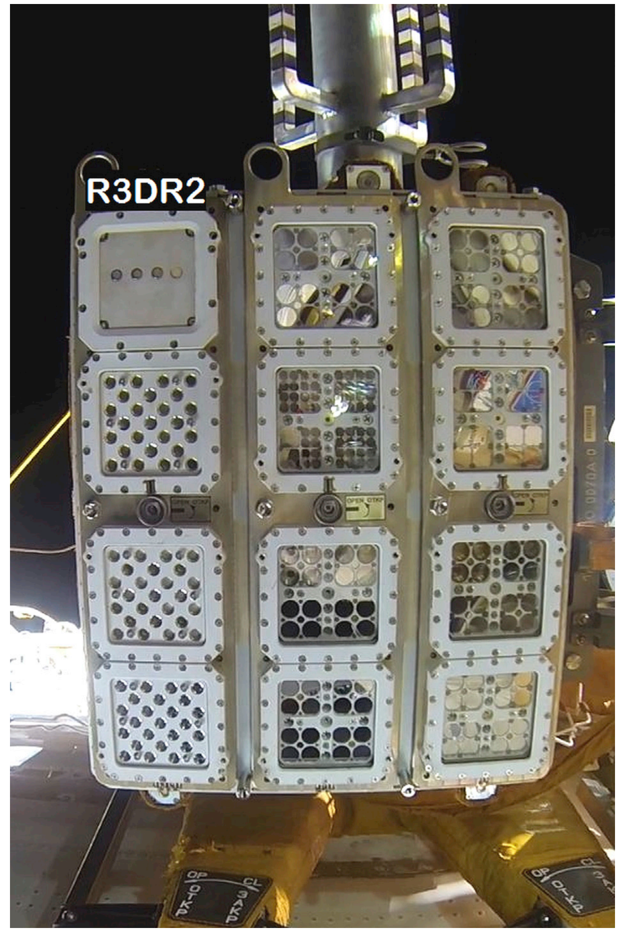


**Fig. 1.** External view of the R3DR2 instrument as mounted on the EXPOSE-R2 facility. (Picture taken by the Russian cosmonauts G. Pedalka and M. Kornienko on August 15th, 2015 during an EVA to examine the EXPOSE-R2 facility outside the Russian "Zvezda" module.) (Picture credit ESA/RKA).

The R3DR2 instrument is a Liulin type (Dachev et al., 2002, 2015a) deposited energy spectrometer (DES) containing: one semiconductor detector (Hamamatsu (S2744-08) PIN diode 2 cm$^2$ area, 0.3 mm thick), one charge-sensitive preamplifier, 2 microcontrollers and serial interface of RS425 toward the EXPOSE-R2 facility. Pulse analysis technique is used to obtain of the deposited energy spectrum, which further is used for the calculation of the absorbed dose and the flux in the silicon detector. The two microcontrollers, through specially developed firmware, manage the unit.

The instrument is a successor of the MDUs, developed and used in the Dosimetric Mapping-E094 experiment (Reitz et al., 2005) on the US Laboratory module of the ISS as a part of the Human Research Facility in May–August, 2001 (Dachev et al., 2002). The main purpose of this experiment was to investigate the dose rate distribution inside the ISS. The obtained data were used for the statistical validation of the high-charge and energy (HZE) transport computer (HZETRN) code (Wilson et al., 2007; Nealy et al., 2007; Slaba et al., 2011) and for the validation of the New Trapped Environment AE9/AP9/SPM model at Low Earth Orbit (Badavi, 2014).

The R3D/E/R radiation environment spectrometer-dosimeters on the ESA EXPOSE-E/R platforms were collaboratively developed by Bulgarian and German teams (Häder and Dachev, 2003; Häder et al., 2009). The current R3DR2 spectrometer-dosimeter onboard the ISS is the same instrument that flew in the EXPOSE-R facility from 2009 to 2010. The extension R2 is given to distinguish the data from the two different EXPOSE missions - EXPOSE-R (1) and EXPOSE-R2.